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The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second order and residual first-order Doppler shifts. To this end we study suitable frequency reference transitions in ions which are stored on electromagnetic traps and cooled by radiation pressure to less than 1K.

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Summary of Work on

"COOLED ION FREQUENCY STANDARD"

(FY 91)

submitted to

Office of Naval Research

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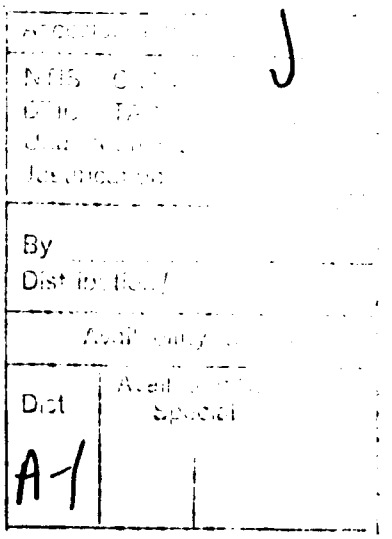

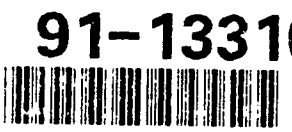

Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present methods for high resolution spectroscopy and frequency standards--the second order and residual first-order Doppler shifts. To this end, we study suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to < 1K.

Scientific Problem

The scientific problems are (1) to find ways to suppress second order and residual first order Doppler shifts in atomic spectroscopy in a fundamental way--by substantially reducing the kinetic energy of ions stored ion electromagnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems (i.e., systematic effects) generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately 2 parts in 10^{14}.

Scientific and Technical Approach

Laser cooling is employed on all experiments in order to suppress Doppler shifts. Temperatures as low as 40 μK have been achieved and temperatures less than 0.1K are routinely achieved. To avoid light shifts on "clock" transitions we investigate "sympathetic cooling" where one ion species is laser cooled and by Coulomb collisions cools another ion species of spectroscopic interest. We continue experiments on Mg^+ and Be^+ in order to study generic problems with traps since these ions are easier to laser cool. We are conducting separate experiments for Hg^+ ions. These experiments have the goal of realizing a frequency standard with 10^{-15} or better accuracy.

I. Summary of progress since Oct. '90.

1. $^9Be^+$ hyperfine pressure shift. We have conducted experiments to identify the cause of the large pressure shift we discovered previously. We have measured the pressure shift of the $^9Be^+$ hyperfine clock transition due to various gasses which are known to be in the kind of vacuum system we use. CH_4 gave a large anomalous shift, H_2, N_2, O_2, H_2O, CO, CO_2, He, and Ar gave no anomalous shift.
2. Linear Paul Trap and High Resolution Microwave Spectroscopy of Hg^+ : "Strings" and more complicated crystalline structures of laser-cooled ions have been observed in an rf trap with linear geometry. This trap should give, for many stored ions, the same small Doppler shifts as achieved for single ions in a Paul trap of more conventional quadrupole geometry. Signal-to-noise ratio will be increased due to the larger numbers of ions. The $^{199}Hg^+$ 40.5 GHz microwave resonance has been detected using microwave/laser double resonance detection. Linewidths of about 0.2 Hz have been observed.
3. Penning Trap Density Limitations: We have identified a mechanism which limits the density for ions in a Penning trap. This limit is caused by a static-field-axial-asymmetry-induced plasma heating resonance which

depends on density and trapping parameters. This will have implications for the large scale storage of partices in Penning traps such as the storage of antiprotons. A physical review letter has been recently published and further measurements and theoretical analysis are underway.

4. Search for anomalous spin-dependent forces using $^9Be^+$ hyperfine spectroscopy: By examining the "clock" transition in $^9Be^+$, we have been able to place upper limits on the strength of anomalous dipole-monopole and dipole-dipole couplings for the electron and neutron.
5. Theory of Sisyphus cooling for a bound atom (ion): Sisyphus cooling for a trapped ion has been theoretically investigated (D. J. Wineland, with J. Dalibard and C. Cohen-Tannoudji) and submitted for publication.
6. Observation of "Atomic Projection" noise: We have observed, in a clear way, the noise in spectroscopic measurements due to fluctuations in the number of atoms (ions) which make the transition when resonance radiation is applied. This fundamental source of noise is in addition to other sources of noise observed previously.
7. Measurement of $g_J(Mg^+)$: The electronic g-factor of $^{26}Mg^+$ has been measured relative to $^9Be^+$ to a precision of about 10^{-8}. With our past measurement of the $^9Be^+$ g-factor, we can determine the magnesium g-factor to a precision of 1.6 parts in 10^7. Comparison with theory is made.
8. Synchrotron Frequency Divider: High order nonlinear excitation of the motion of a single electron has been studied. Studing the excitation of the magnetron motion has proven fruitful because of the relative insensitivity to magnetic field fluctuations.
9. Observation of time varying radiation pressure forces: The effects of time varying dipole forces and radiation pressure forces on trapped ions were studied theoretically and experimentally.
10. Hg^+ optical frequency standard: Efforts to stabilize the 282 nm laser for the quadrupole transition in $^{199}Hg^+$ have resulted in linewidths less than 25 Hz. Efforts to apply this radiation to the ion have been hampered because of the limited lifetime ($\simeq$ 1 hr) of Hg^+ ions in the trap (due to dimer formation). Recent effort has been shifted to developing an apparatus with cryogenic pumping which should eliminate ion loss problems and also prevent possible pressure shift problems encountered in the $^9Be^+$ experiments
11. Laser Cooled Refrigerator and Detector: A coupled trap is under construction. This first experiment is designed to "sympathetically" cool electrons which are stored in one trap by electronically coupling them to laser-cooled ions which are contained in another trap.

II. PUBLICATIONS ETC., FY '91

A. PAPERS PUBLISHED IN REFEREED JOURNALS

1. "Quantum-limited cooling and detection of radio-frequency oscillations by laser-cooled ions," D. J. Heinzen and D. J. Wineland, Phys. Rev. A42, 2977 (1990).
2. "Comment on "Nonlinear magneto-Optics of Vacuum: Second Harmonic Generation'," M. G. Raizen and B. Rosenstein, Phys. Rev. Lett. 65, 2744

(1990).

3. "Rotational equilibria and low-order modes of a non-neutral plasma," D. J. Heinzen, J. J. Bollinger, F. L. Moore, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 66, 2080 (1991).
4. "Reply to "Comment on the Quantum Zeno effect'," W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, Phys. Rev. A43, 5168 (1991).
5. "Progress at NIST towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, and M. G. Raizen, IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control 37, 515 (1990).
6. "A 303-MHz Frequency Standard Based on Trapped Be^+ Ions," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, IEEE Trans. on Instrum. and Meas. 40, 126 (1991).
7. "Search for anomalous spin-dependent forces using stored ion spectroscopy," D. J. Wineland, J. J. Bollinger, D. J. Heinzen, W. M. Itano, and M. G. Raizen, Phys. Rev. Lett. 67, 1735 (1991).
8. "Atomic Ion Frequency Standards," W. M. Itano, Proc. of the IEEE, Special Issue on Time and Frequency, 79, 936 (1991).

B. PAPERS SUBMITTED TO REFEREED JOURNALS (not yet published)

1. "Sisyphus cooling of a bound atom," D. J. Wineland, J. Dalibard, and C. Cohen-Tannoudji, submitted to JOSA B.
2. "Electrostatic Modes of a Penning Trap Plasma," J. J. Bollinger, et al., submitted to Phys. Rev. A.
3. "Linear Trap for High Accuracy Spectroscopy of Stored Ions," M. G. Raizen, J. C. Bergquist, J. M. Gilligan, W. M. Itano, and D. J. Wineland, J. Modern Optics, special issue on the Physics of Trapped Ions, ed. by R. Blatt, P. Gill, and R. C. Thompson, submitted.
4. "Experiments with ionic crystals in a linear Paul trap," M. G. Raizen, J. M. Gilligan, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. A, submitted.
5. "The measurement of time and frequency," W. M. Itano and N. F. Ramsey, Sci. Am., submitted.

C. BOOKS (and sections thereof) PUBLISHED

1. "Quantum Optics of Single, Trapped Ions," W. M. Itano, J. C. Bergquist, F. Diedrich, and D. J. Wineland, in Coherence and Quantum Optics, ed. by J. H. Eberly et al., (Plenum, New York, 1990) p. 539.
2. "Test of the Linearity of Quantum Mechanics by RF Spectroscopy of the $^9Be^+$ Ground State," D. J. Heinzen, J. J. Bollinger, W. M. Itano, S. L. Gilbert, and D. J. Wineland, ibid., p. 479.
3. "Progress at NIST on Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, M. G. Raizen, and C. S. Weimer, proc. 4th European Frequency and Time Forum, Neuchatel, 1990,
4. "The Quantum Zeno Effect," W. M. Itano, in Physics News in 1990, ed. by Phillip W. Schewe (American Inst. of Physics, New York, 1990), p. 17.
5. "Clocks, Atomic and Molecular," J. A. Barnes and J. J. Bollinger,

Encyclopedia of Physics, ed. by R. G. Lerner and G. L. Trigg, (VCH Publishers, Inc., New York, 1991).

6. "Trapped Ion Frequency Standards," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, C. H. Manney, F. L. Moore, M. G. Raizen, and C. S. Weimer, proc. 22nd Ann. Precise Time and Time Interval (PTTI) Applications and Planning Meeting, ed. by R. L. Sydnor, (NASA Conf. Publ. 3116, 1991), p. 53.
7. "Single Ion Optical Spectroscopy," J. C. Bergquist, W. M. Itano, F. Elsner, M. G. Raizen, and D. J. Wineland, in Light Induced Kinetic Effects on Atoms, Ions and Molecules, ed. by L. Moi, S. Gozzini, C. Gabbanini, E. Arimondo, and F. Strumia, (ETS Editrice, Pisa, 1991), p. 291.

D. BOOKS (and sections thereof) SUBMITTED

1. "Atomic Physics Tests of Nonlinear Quantum Mechanics," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, proc. of the 12th International Conference on Atomic Physics, World Scientific, to be published.
2. "Penning trap experiments at the University of Washington and at NIST in Boulder," F. L. Moore, proc. of the International Symposium on "Cooler Rings and Their Applications," Tokyo, Nov., 1991 (World Scientific, Singapore).
3. "Single Ion Optical Frequency Standard," J. C. Bergquist, W. M. Itano, F. Elsner, M. G. Raizen, and D. J. Wineland, submitted to the proc of the Symposium on Frequency Control, Los Angeles, CA, May, '91.
4. "Recent Experiments on Trapped Ions at the National Institute of Standards and Technology," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, F. L. Moore, J. M. Gilligan, M. G. Raizen, D. J. Heinzen, C. S. Weimer, and C. H. Manney, Proc. of the Enrico Fermi Summer School on "Laser manipulation of atoms and ions," July, '91, Varenna, Italy, submitted.
5. "High Resolution Atomic Spectroscopy of Laser-Cooled Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, F. L. Moore, J. M. Gilligan, M. G. Raizen, C. S. Weimer, and C. H. Manney, ibid.
6. "Laser Cooling of Trapped Ions," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, ibid.
7. "Atomic physics tests of nonlinear quantum mechanics," J. J. Bollinger, D. J. Heinzen, W. M. Itano, S. L. Gilbert, and D. J. Wineland, Santa Fe conference on Quantum measurements, July, '91.
8. "Single ion spectroscopy," J. C. Bergquist, D. J. Wineland, W. M. Itano, F. Diedrich, M. G. Raizen, and F. Elsner, SPIE proc.

E. INVITED PRESENTATIONS AT TOPICAL OR SCIENTFIC/TECHNICAL SOCIETY CONFERENCES

1. OSA Annual Meeting, Boston, MA, Nov. '90, J. C. Bergquist.
2. International Symposium on Cooler Rings and Their Applications, Tokyo, Japan, Nov., '90, F. L. Moore.
3. 1990 Precise Time and Time Interval (PTTI) meeting, Tyson's corner, Va.,

Dec. 1990, D. J. Wineland.

4. 21st Winter Conference on Quantum Electronics, Snowbird, Utah, Jan. '91, J. C. Bergquist.
5. OE/LASE '91 Symposium on Laser Spectroscopy, SPIE, Los Angeles, CA, Jan. '91, J. C. Bergquist.
6. XIthe Moriond Workshop, Tests of Fundamental Laws in Physics, Les Arcs, Savoie, France, Jan. '91, D. J. Wineland.
7. AAAS Meeting - symposium on Quantum Mechanics of Single Atoms, Washington, D. C., Feb. '91, D. J. Heinzen.
8. APS Spring meeting, Washington, D. C., April, '91, W. M. Itano.
9. Symposium on Frequency Control, Los Angeles, CA, May, '91, J. C. Bergquist.
10. Foundations of Quantum Mechanics, Santa Fe, NM, May, '91, J. J. Bollinger.
11. Workshop on Physics with Penning traps, Lertorpet, Sweden, June, '91, J. J. Bollinger.
12. Gordon Conference on Atomic Physics, Wolfboro, NH, July, '91, D. J. Wineland.
13. Enrico Fermi Summer School on Laser Manipulation of Atoms and Ions, Varenna, Italy, July, '91, D. J. Wineland.
14. Workshop in Honor of E. C. G. Sudarshan, Austin Texas, Sept., '91, W. M. Itano.

F. OTHER INVITED TALKS (colloquia, etc.)

1. Univ. of Colorado, Boulder, Co., Oct. '90, W. M. Itano
2. U. of Texas, Austin, Texas, Oct. '90, M. G. Raizen
3. Univ. of Alberta, Edmonton, Canada, Oct. '90, W. M. Itano
4. Argonne National Lab., Argonne, Ill., Oct. '90, J. J. Bollinger
5. Univ. of Colorado, Boulder, CO, Oct. '90, D. J. Wineland
6. Univ. of British Columbia, Vancouver, Canada, Nov. '90, W. M. Itano
7. U. C., Berkeley, Berkeley, Ca., Nov. '90, M. G. Raizen
8. Tokyo Metropolitan Univ., Tokyo, Japan, Nov. '90, F. L. Moore
9. Univ. of Electrocommunications, Tokyo, Nov. '90, F. L. Moore
10. Inst. of Nuclear Study, Tokyo, Nov. '90, F. L. Moore
11. Tohoku Univ., Sendai, Japan, Nov. '90, F. L. Moore
12. RCNP, Osaka, Japan, Nov. '90, F. L. Moore
13. Stanford Univ., Stanford, Ca., Nov. '90, M. G. Raizen
14. Weizmann Inst. of Science, Rehovot, Israel, Nov. '90, M. G. Raizen
15. Ben-Gurion Univ., Beer Sheva, Israel, Nov. '90, M. G. Raizen
16. Notre Dame University, IN, Nov. '90, J. J. Bollinger
17. Harvard Univ., Cambridge, MA, Nov. 1990, D. J. Wineland
18. Univ. of Colorado, Boulder, CO, Nov. '90, J. J. Bollinger
19. Johns Hopkins Univ., Applied Physics Lab., Laurel, MD, Dec. '90
20. Univ. of Rochester, Rochester, New York, Dec. '90, M. G. Raizen
21. Yale Univ., New Haven, CT, Jan. '91, J. J. Bollinger
22. Univ. of Oregon, Eugen, Oregon, Feb. '91, M. G. Raizen
23. Colorado School of Mines, Golden, CO., Feb. '91, M. G. Raizen
24. Stanford Univ., Stanford, CA, Feb. '91, D. J. Wineland
25. Univ. of Colorado, Denver, CO., Mar. '91, M. G. Raizen

26. Univ. of Texas, Austin, Texas, June, '91, M. G. Raizen
27. Univ. São Paulo, São Carlos, Brazil, 5 lectures, Aug. '91, D. J. Wineland.
28. Cornell Univ., Ithaca, N. Y., Sept. '91, D. J. Wineland.

G. HONORS, AWARDS,PRIZES

1. APS Fellowship, W. M. Itano
2. APS Fellowship, J. J. Bollinger
3. William F. Meggers Award (OSA), D. J. Wineland